1917
K735

Knight

Magnetic Reluctance of Joints in Laminated Iron Circuits

MAGNETIC RELUCTANCE OF JOINTS IN LAMINATED IRON CIRCUITS

BY

ABNER RICHARD KNIGHT

M. E., OHIO STATE UNIVERSITY, 1909

THESIS

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE

DEGREE OF
MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1917

1917
K735

UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

May 31, 1917

24 Dec. 17 Gilley

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Abner Richard Knight,

ENTITLED Magnetic Reluctance of Joints in Laminated Iron Circuits

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Electrical Engineering.

Ellery B. Paine
In Charge of Major Work

Ellery B. Paine
Head of Department

Recommendation concurred in:

Committee on Final Examination

376348

Digitized by the Internet Archive
in 2013

http://archive.org/details/magneticreluctan00knig

TABLE OF CONTENTS.

		page
I	Introduction	1
II	Method	2
III	Description of Apparatus	7
IV	Sample Calculations	8
V	Results of Tests	10
VI	Conclusions	12

Tables

I	Reluctance of magnetic circuits by the alternating current method. Laminations stacked in groups of three	16
II	Reluctance of magnetic circuits by the ballistic method. Laminations stacked in groups of three	19
III	Reluctance of magnetic circuits by the ballistic method. Laminations stacked singly	21

Graphs

I	Calibration of galvanometer	14
II	Magnetization curve using different calibration curve	15
III	Reluctance of circuits by the A.C method. Laminations in groups of three	17
IV	Comparison of results on 3/4" lap joint	18
V	Reluctance of circuits by the ballistic method. Laminations stacked in groups of three	20
VI	Reluctance of circuits by the ballistic method. Laminations stacked singly	22
VII	Equivalent air gap lengths	23

I Introduction.

In the early days of transformer design little attention was paid to any factor not affecting the efficiency or the regulation of the transformer. Because of the fact that the magnetizing current does not represent an energy loss and also because a reasonably low core loss usually bears a value of magnetizing current that is not excessive it did not receive any particular attention or study. A few years ago however the users of transformers awoke to the fact that a small magnetizing current, while not materially improving the operating characteristics of the transformer itself, would be advantageous from the stand point of the operation of the distribution system because of the reduced line loss during light load times and also because of the beneficial effect of the improved power factor of the system upon the generating equipment.

When this fact was recognized more study was given to the design of the transformer core with the object of reducing the magnetizing current. In order to predetermine the magnetizing current the magnetization curve of the iron was necessary and also data on the reluctance of the joints introduced into the magnetic circuit by the use of form wound coils. An examination of the available literature on transformer design or on laminated iron circuits did not throw much light on the question, mention being found in only one place*

*See "A Treatise on the Transformer" by Bohle & Robertson p 15 ff

and the information given there was very meager. For this reason it was decided to carry on a series of tests with the object of determining the reluctance of joints of various kinds.

II Method.

The method used was, in general, to determine the total reluctance of a magnetic circuit which did not contain any joints and of a circuit of the same material containing two joints of the given kind and charge the difference to the joints. The reluctance of the circuit was found in two ways, first, what might be called the alternating current method, and second, the ballistic method. For the alternating current method two windings were placed on the core and an electromotive force from a sine wave alternator impressed upon one of them. Readings were made of the volts, amperes, and watts supplied to this winding. The other winding was used for the purpose of measuring the induced voltage. From the induced voltage the maximum value of the flux was obtained as follows:

Since the wave of the voltage was sinusoidal the flux wave was also sinusoidal and can be expressed as

$$\varphi = \varphi_{max} \sin \omega t \quad \cdots\cdots\cdots\cdots (1)$$

The induced voltage in any circuit is

$$e = -n\frac{d\varphi}{dt} \times 10^{-8} \quad \cdots\cdots\cdots\cdots (2)$$

where n is the number of turns in the winding.

Differentiating (1) with respect to t gives

$$\frac{d\varphi}{dt} = \omega\varphi_{max} \cos \omega t \quad \cdots\cdots\cdots\cdots (3)$$

$$= 2\pi f\varphi_{max} \cos \omega t \quad \cdots\cdots\cdots\cdots (4)$$

since $\omega = 2\pi f$ f being the frequency.

Substituting (4) into (2) gives

$$e = -2\pi f n \varphi_m \cos \omega t \times 10^{-8}$$

The effective value of the emf is

$$E = \frac{2\pi f n \varphi_m}{\sqrt{2}} \times 10^{-8} = 4.44 f n \varphi_m \times 10^{-8} \quad \cdot \cdot \quad (5)$$

Solving (5) for φ_m gives

$$\varphi_m = \frac{E \times 10^8}{4.44 f n} \quad \text{maxwells}$$

From the input amperes and watts and the induced emf the magnetomotive force acting on the circuit can be determined as follows;

Let I_{oo} be the total current as read on the ammeter

" I_c " " core loss current

" I_m " " magnetizing current

" E " " induced emf

" W " " core loss as read on the wattmeter

The core loss current can be found directly from E and W and is

$$I_c = \frac{W}{E}$$

Since I_c and I_m are 90° out of phase with each other and their vector sum is equal to I_{oo}, I_m can be found from I_{oo} and I_c and is

$$I_m = \sqrt{I_{oo}^2 - I_c^2}$$

Knowing I_m and the number of turns in the winding, the magnetomotive force is

$$F = \frac{\sqrt{2} \times 4\pi n I_m}{10} \quad \text{gilberts}$$

The reluctance of the circuit is

$$R = \frac{F}{\varphi_m} \quad \text{oersteds}$$

A diagram of the connections for this method is shown in Fig 1.

For the determination of the reluctance of the circuit by the ballistic galvonometer method the circuit was connected as shown in Fig 2 page 4. A direct current flowing in the primary winding

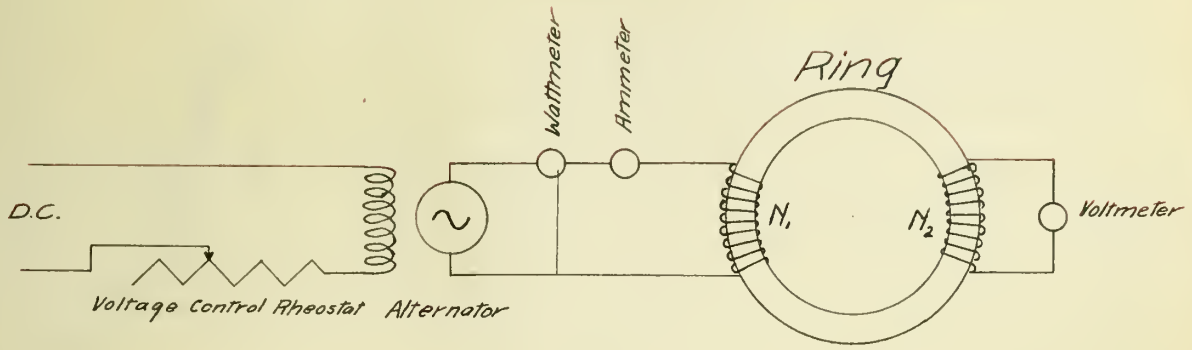

Ring
Wattmeter
Ammeter
D.C.
N_1
N_2
Voltmeter
Voltage Control Rheostat
Alternator

Fig. 1

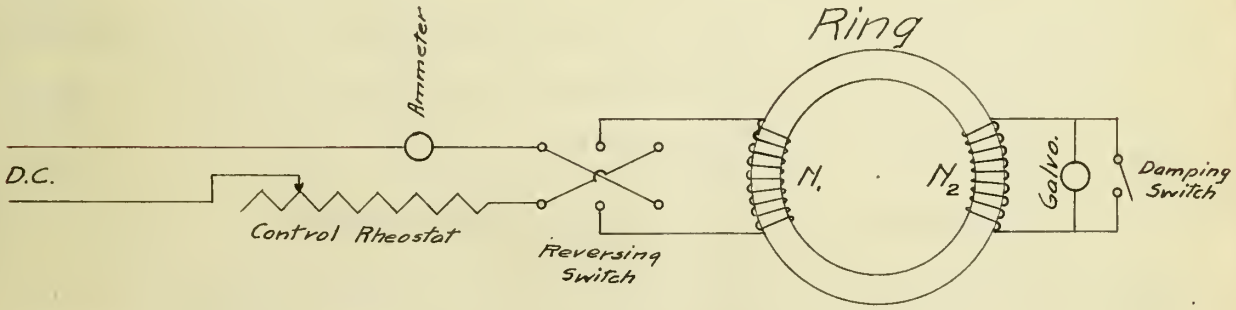

Ring
Ammeter
D.C.
N_1
N_2
Galvo.
Damping Switch
Control Rheostat
Reversing Switch

Fig 2

N_1 produces a magnetomotive force F which causes a flux to be established in the iron. This condition is represented by the point A on the hysteresis loop of Fig 3. If the current is reversed, the magnetomotive force is reversed and the flux is reversed to the point B, moving along the left hand side of the loop. On reversing the current a second time the flux returns to A by the right hand side of the loop. If a smaller value of current is used the flux will pass around the loop A'B'. The locus of the points A, A' etc is the mean magnetization curve of the iron. For the determination of the mean magnetization curve it is not necessary to obtain any points on the hysteresis loop other than the end points. This can be done easily, because, first, the throw of the galvanometer is proportional to the change in flux turns in the circuit to which it is connected,* and second, the flux represented at A is numerically equal to that at B. Thus from the throw of the galvanometer upon reversal of the current the total change in flux turns is known, and dividing this change by $2N_2$ gives the flux at A. From the current and the turns N_1 the magnetomotive force can be calculated, and the reluctance in oersteds is then found by dividing the magnetomotive force by the flux.

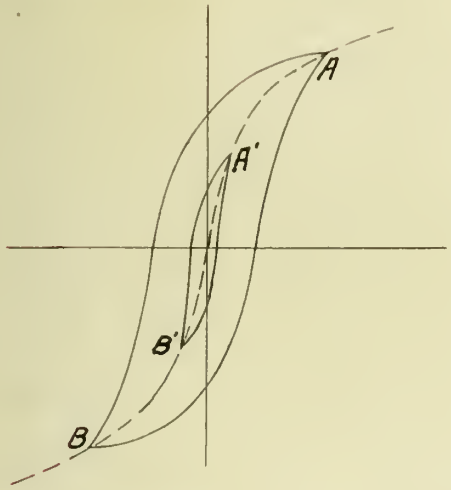


Fig 3

In order to know the change in flux turns represented by any given throw of the galvanometer it was connected to the secondary of the air core coil used by the Experiment Station for the calibration

For the theory of the action of the ballistic galvanometer see "Practical Electricity and Magnetism" by Henderson p 228 ff.

of their instruments.* The magnetization curves obtained using this calibration differed more from those obtained by the alternating current method than was thought reasonable and a second calibration was made using as a standard a Grassot fluxmeter, and as a magnetic circuit in which to reverse the flux the iron circuit under test. This latter calibration gave results, which, while not checking exactly with those obtained by the alternating current method, were as close as could be expected considering the difference between the two methods. The reason for the difference in the calibration of the galvanometer in the two cases lies in the fact that the flux in the iron does not change instantaneously upon reversal of the current because of the eddy currents induced in the iron by the changing flux. Since the flux through the air core coil changes instantaneously when the current is reversed the entire electric charge induced by the change passes through the galvanometer coil before it starts to move. The calibration obtained in this way will not show the total change in flux in the iron because only part of the change is completed when the galvanometer coil starts to move. This error is such as to make the flux change appear smaller than is actually the case. The two calibrations are shown, as a matter of interest, on page 14 and the magnetization curves for one test by the two calibrations are shown on page 15.

After the mean magnetization curves were obtained the reluctance of the different circuits were calculated and curves were plotted between flux density and total reluctance of the circuit. From these curves the reluctance of the joint was found by subtracting the reluc-

*For a complete description of the air core coil and the theory of its use see Bulletin #72 University of Illinois Engineering Experiment Station, Magnetic and Other Properties of Electrolytic Iron Melted in Vacuo, by T.D.Yensen.

tance of the continuous ring for any given flux density from that of the split ring for the same flux density. In order to make the results applicable to any circuit the reluctance was put into terms of an equivalent air gap length. By this is meant an air gap having the same cross sectional area as the net area of the iron, so that the flux density is the same as the apparent flux density in the iron, and the length such that it will have the same reluctance as the actual joint.

III Description of Apparatus.

The material used in the magnetic circuit was No. 29 gauge sheet silicon steel. The sheets averaged .01456" thick with the scale and .0181" thick without the scale. This gives a ratio of gross thickness to net thickness of .09 . The sheets were punched into rings 15" outside diameter and 9" inside diameter; after punching they were subjected to the regular annealing process given to commercial transformer stamprings.

The continuous rings were wound with 200 turns of No. 18 B S gauge wire for the primary winding, 100 turns of No. 18 B S gauge wire for the secondary for the alternating current method and 16 turns of No. 25 B S gauge wire for the secondary for the ballistic method. For the tests on the split rings four bobbins were made each having 50 turns of No.18 B S gauge wire for the primary, 25 turns of No.18 B S gauge wire for secondary for the alternating current method, and four turns of No. 25 B S gauge wire for the secondary for the ballistic method. For the alternating current method Weston A C instruments which had been carefully calibrated were used. For the ballistic method a Leeds and Northrup galvanometer having a period of 11 seconds

was used to determine the flux and a Weston D'Arsonval type ammeter was used to measure the magnetizing current.

Several types of joints were tested, namely, butt joints, lap joints made by stacking the laminations singly and having average laps of .6",1.2",1.8",2.4", and 7.5", and lap joints made by stacking the laminations in groups of three with the same average laps as above.

IV Sample Calculations

Take as an example of the determination of the reluctance of the circuit by the alternating current method the first values given for the continuous ring in Table I page 16.

Here I_{co} = .4 amperes E = 66.8 volts W = 14.0 watts

$$I_c = \frac{14}{66.8} = .21 \text{ ampere}$$

$$I_m = \sqrt{.4^2 - .21^2} = .34 \text{ ampere}$$

$$F = \sqrt{2} \times .4\pi \times 200 \times .34 = 120.8 \text{ gilberts}$$

$$\Phi_m = \frac{66.8 \times 10^8}{4.44 \times 200 \times 60} = 125,500 \text{ maxwells}$$

and

$$R = \frac{120.8}{125,500} = .00096 \text{ oersted}$$

The circuit consisted of 66 laminations each having a net thickness of .0181". The area is

$$A = 8 \times 66 \times .0181 = 9.59 \text{ square inches}$$

and the flux density is

$$B = \frac{125,500}{9.59} = 48,400 \text{ maxwells per square inch}$$

Take as an example of the calculation of the reluctance of the circuit by the ballistic method the first values given for the continuous ring in Table II page 19.

Here I = .55 ampere and the average deflection = 11.15 cms

Referring to the calibration curve on page 14 it is seen that a deflection of 11.15 cms corresponds to a change in flux turns of 3,880,000. Since there were 16 turns in the secondary winding the flux change was

$$\Delta\phi = \frac{3,880,000}{16} = 242,000$$

and the initial flux was

$$\phi = \frac{242,000}{2} = 121,000 \text{ maxwells}$$

The magnetomotive force was

$$F = .4\pi \times 200 \times .55 = 138 \text{ gilberts}$$

and the reluctance was

$$R = \frac{138}{121,000} = .00114 \text{ oersted}$$

and

$$B = \frac{121,000}{2.59} = 48,500 \text{ maxwells per square inch}$$

After the total reluctance of the circuits with and without the joint were found for the different flux densities curves were plotted showing this relation. See Graph VI page 22. From these curves the reluctance of the joint was found by subtracting the reluctance of the continuous ring circuit from that of the split ring circuit. Having found the reluctance of the joint in this manner the equivalent air gap length was found as follows;

The reluctance of any circuit is

$$R = \frac{l}{\mu A}$$

where l is the length of the path in centimeters, A its area in square centimeters, and μ its permeability.

Transposing, the length of the circuit is

$$l = \mu A R. \text{ centimeters}$$

For the equivalent air gap $\mu = 1$ and $A = 6.59$, therefore the length is

$$l = 6.59 \times R \quad \text{centimeters}$$

As an example of this calculation take the reluctance of the butt joint for a flux density of 65,000 maxwells per square inch. The difference between the total reluctance with and without the joint is, from Graph VI, .00058 oersted. This is the reluctance of two joints so that of one joint is .000265 oersted.

The equivalent length is then

$$l = 6.59 \times .000265 = .00175 \text{ cms}$$

$$= \frac{.00175}{2.54} = .00069 \text{ inch}$$

V Results of Tests

Trouble was experienced in making the tests by the alternating current method because of inability to maintain the speed of the driving motor constant, and it was abandoned in favor of the ballistic method.

A representative set of data obtained by this method for cores assembled by stacking the laminations in groups of three is given on page 16 and the curves from this data are shown on Graph III page 17.

Data for the same joints assembled in the same way, obtained by the ballistic method, is given on page 19 and the resulting curves are shown on Graph V page 20.

It will be noticed in both cases that there is apparently no relation between the length of the lap and its reluctance. It was decided that this was due to the fact that, in spite of all the care that could be exercised in assembling the core, it was not possible to get the ends of all of the laminations butted together, introducing in this way an air gap of considerable relative length into

the circuit. This relation of the laminations of corresponding layers is shown in Fig 4. Because of the gap between the sheets B and B' and C and C' the flux is concentrated in sheet A-A'. This causes the flux density in A-A' to be high and the permeability to be low, almost equal to that of air, so that there is practically an air gap of considerable length in the circuit. If this is the true explanation it would be expected that, in addition to the lack of uniformity in the results for lap joints of different lengths, that the data for the same length of lap would not check if the joint were torn down and rebuilt. This was found to be the case as is shown on Graph IV on page 18.

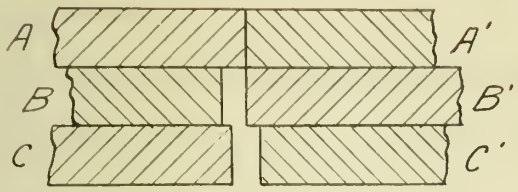


Fig 4

In order to eliminate this trouble the laminations were stacked singly. With this method of stacking it was found that the curves between flux density and reluctance practically coincided for all lengths of lap used except the 7.5" lap. From this fact it may be concluded that the explanation given above is correct. This coincidence of the curves can be explained by a consideration of the flux path across the joint. It is probable that the air gap between the layers is less than that between the ends of the laminations butted together, or at the worst, equal to it; also the area of the path from one lamination to the next one above or below it is many times greater than that of the ends of

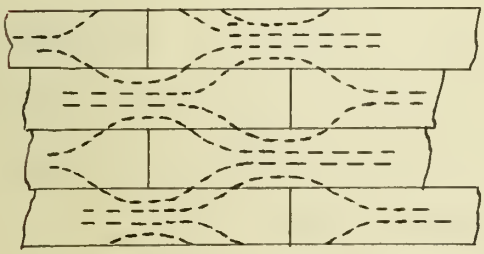


Fig 5

the laminations. Both of these factors would make the path of least reluctance that shown in Fig 5. If this is true it would not be expected that there would be much difference in the reluctance of the joint unless the length of the lap were comparable with the thickness of a sheet. In order to check this conclusion an attempt was made to assemble a joint with an average lap of .05" but it was found impossible to do so with the laminations in the form of rings.

VI Conclusions.

Although the equivalent air gap length was found to increase with the flux density, the variation throughout the working range for transformer cores, 55,000 to 75,000 maxwells per square inch, is not very great. For lap joints it is from .00015" to .00035" with an average value of about .00025" . For the butt joint the variation is not so large and the average value is about .00075".

From the irregularity of the results obtained with the core assembled in groups of three it is seen that the possibility of getting a poor joint with this method of stacking is very good, even when great care is taken in stacking the laminations. On the other hand if the sheets are stacked singly the joint is uniformly good. This would lead one to the conclusion that for a lap joint stacked singly a carelessly assembled core would not result in a joint of relatively high reluctance. The labor cost, however, for stacking singly is much higher than for the group stacking. It was noticed that it required two men about twenty minutes to assemble the core when stacking the laminations in groups of three and about forty five minutes when stacking

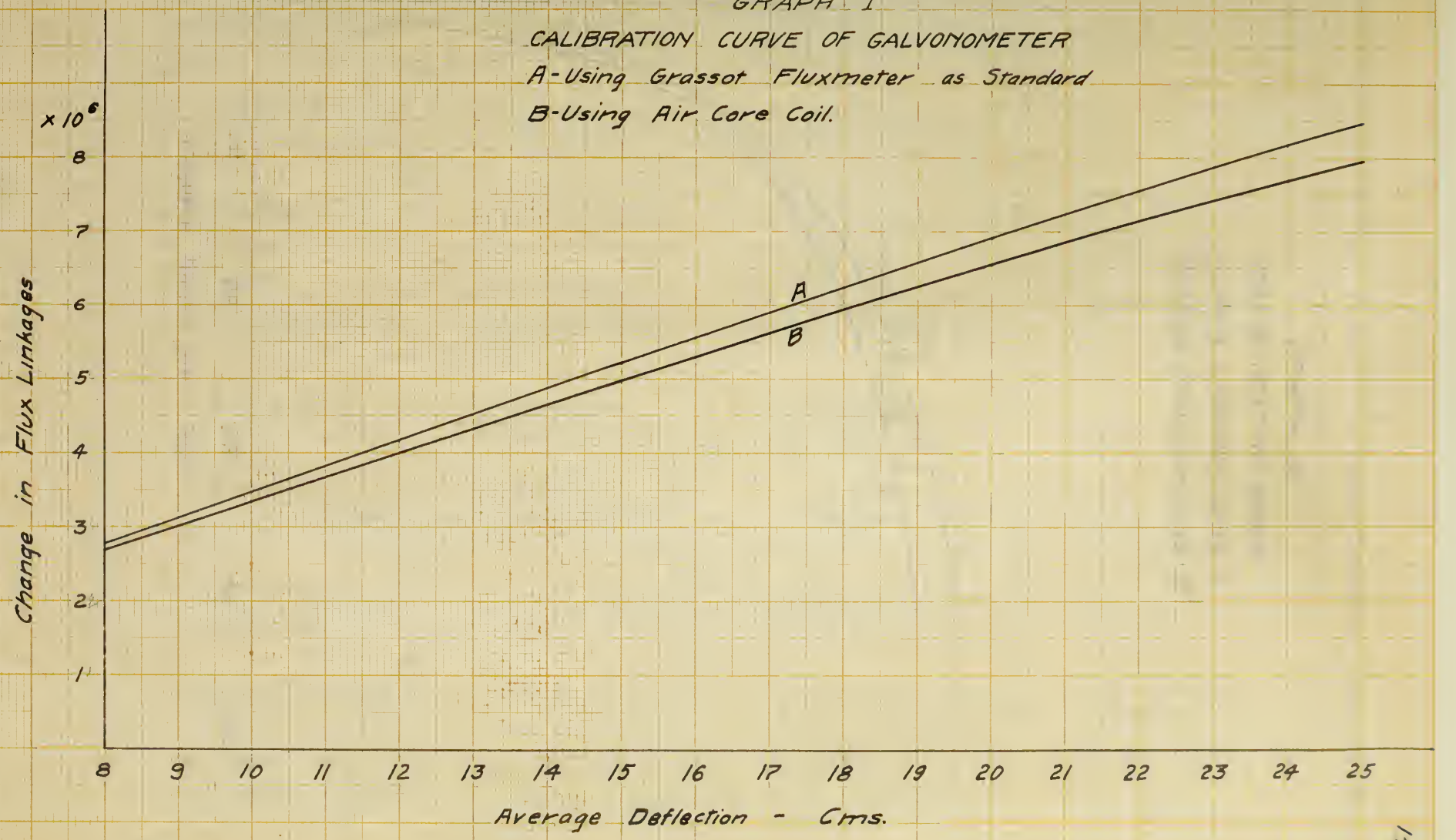
them singly. The butt joint took one man about five minutes to assemble and required less effort to insure a good joint.

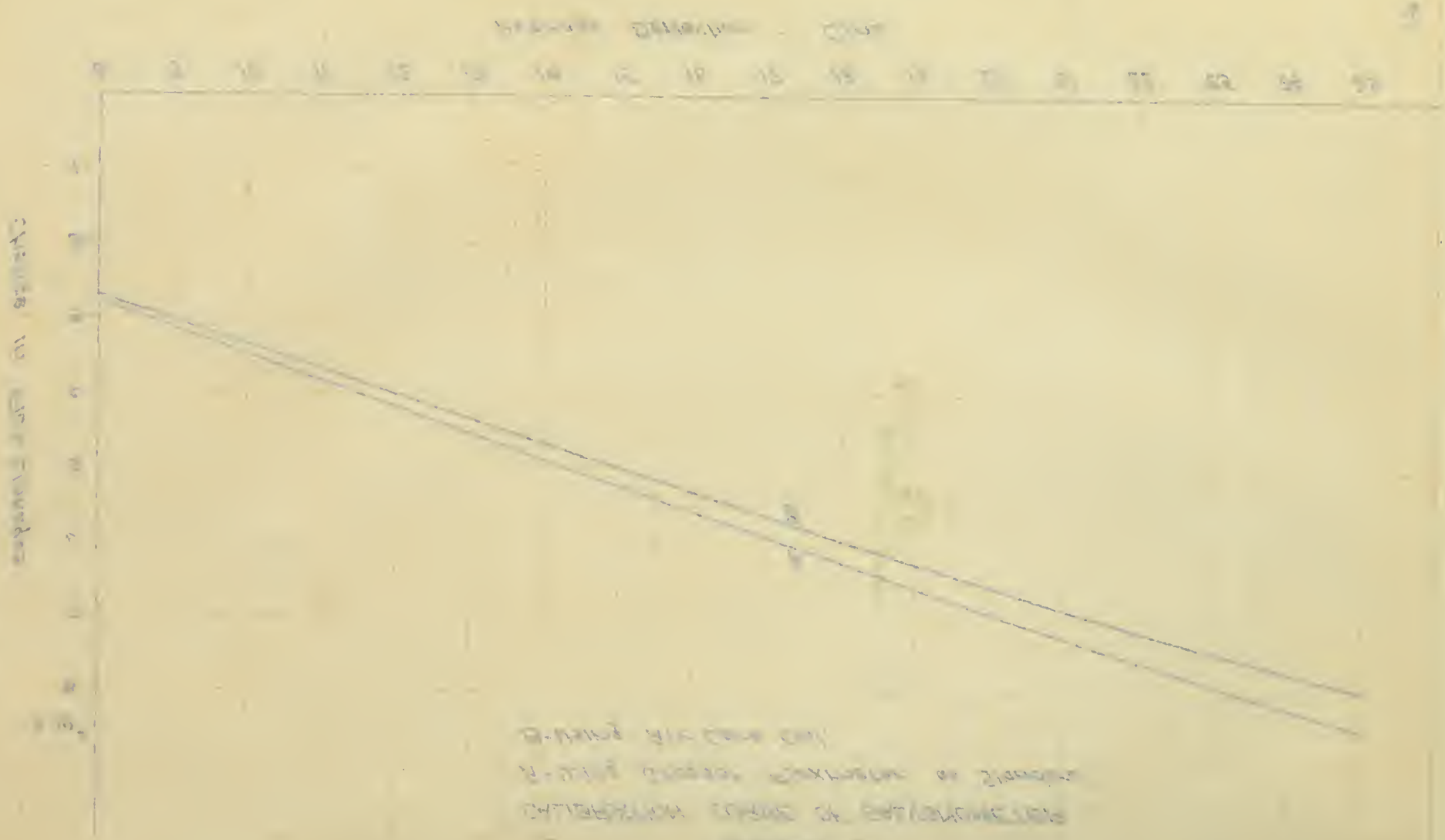
I am of the opinion that if a line of transformers were designed with butt joints, allowing a little more magnetizing current for the joints and working the iron at a lower density to compensate for it, that the saving in labor cost of assembling the core would more than offset the increased cost of iron and copper needed. This type of core construction would be desirable from the user's standpoint because of the comparative ease with which a burned out coil could be replaced.

Fig 6

It was intended to test a butt joint in which the cross sectional area is increased by cutting the sheets in the manner shown in Fig 6 but the material was not received in time to do so.

This question of the comparative cost will furnish the basis for further investigation.


GRAPH I
CALIBRATION CURVE OF GALVONOMETER
A-Using Grassot Fluxmeter as Standard
B-Using Air Core Coil.
x 10^6
Change in Flux Linkages
8
7
6
5
4
3
2
1
A
B
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
Average Deflection - Cms.



GRAPH II

MAGNETIZATION CURVE

A - Using Calibration Curve "A"

B - Using Calibration Curve "B"

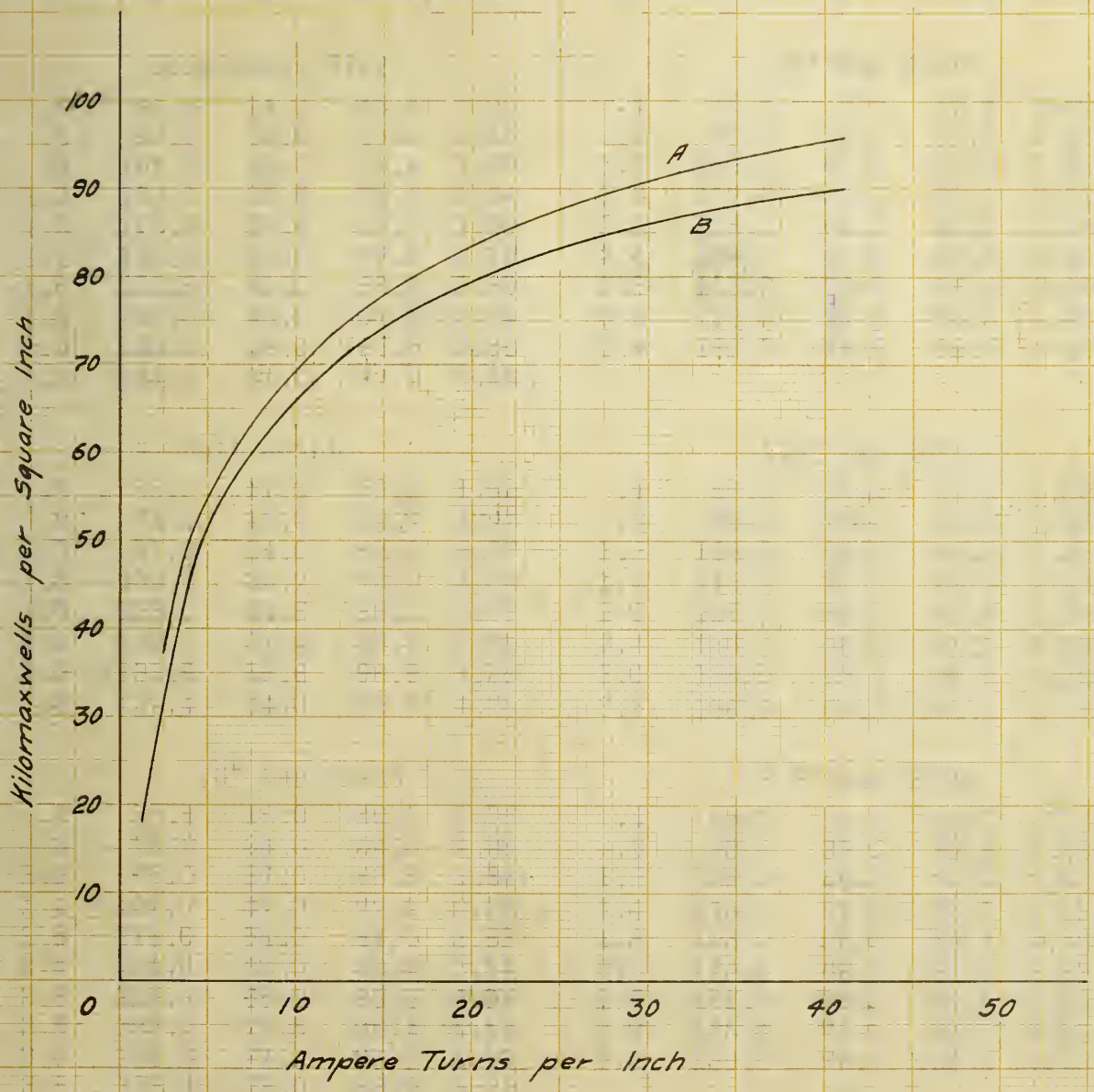


TABLE I

RELUCRANCE OF MAGNETIC CIRCUITS BY THE ALTERNATING CURRENT METHOD

Lap joints assembled with three laminations per bundle.

Amperes	Volts	Watts	Flux Density Kilomaxwells per Sq. In.	Reluctance Millioersteds
	Continuous Ring			
.4	66.8	14.0	46.4	.96
.6	90.0	23.0	65.2	1.13
.8	101.2	28.0	73.4	1.40
1.0	110.0	32.5	79.6	1.64
1.2	115.6	35.6	83.7	1.90
1.4	120.2	38.5	87.1	2.12
1.6	123.8	41.0	89.6	2.39
1.8	126.0	43.5	91.3	2.64
2.0	129.0	46.0	93.5	2.88
2.5	134.0	51.0	97.6	3.48
	Butt Joint			
.6	55.0	11.0	39,8	1.91
.8	72.8	17.0	52.7	1.97
1.0	87.0	24.0	63.0	2.07
1.5	109.0	35.7	79.0	2.54
2.0	123.0	44.5	89.1	2.97
2.5	129.0	51.4	93.5	3.61
3.0	133.8	58.6	96.9	4.18
3.5	137.4	64.0	99.5	4.75
	.6" Lap Joint			
.4	56.4	16.0	40.9	1.06
.6	75.2	24.0	54.5	1.28
1.0	95.0	37.0	68.8	1.84
1.4	107.0	47.0	77.5	2.35
1.8	116.0	54.0	84.0	2.83
2.4	124.8	63.0	90.4	3.54
2.8	129.4	68.0	93.8	4.02
3.2	133.0	72.5	96.4	4.58
3.6	138.0	77.5	97.8	5.00
3.8	136.4	78.0	98.9	5.21

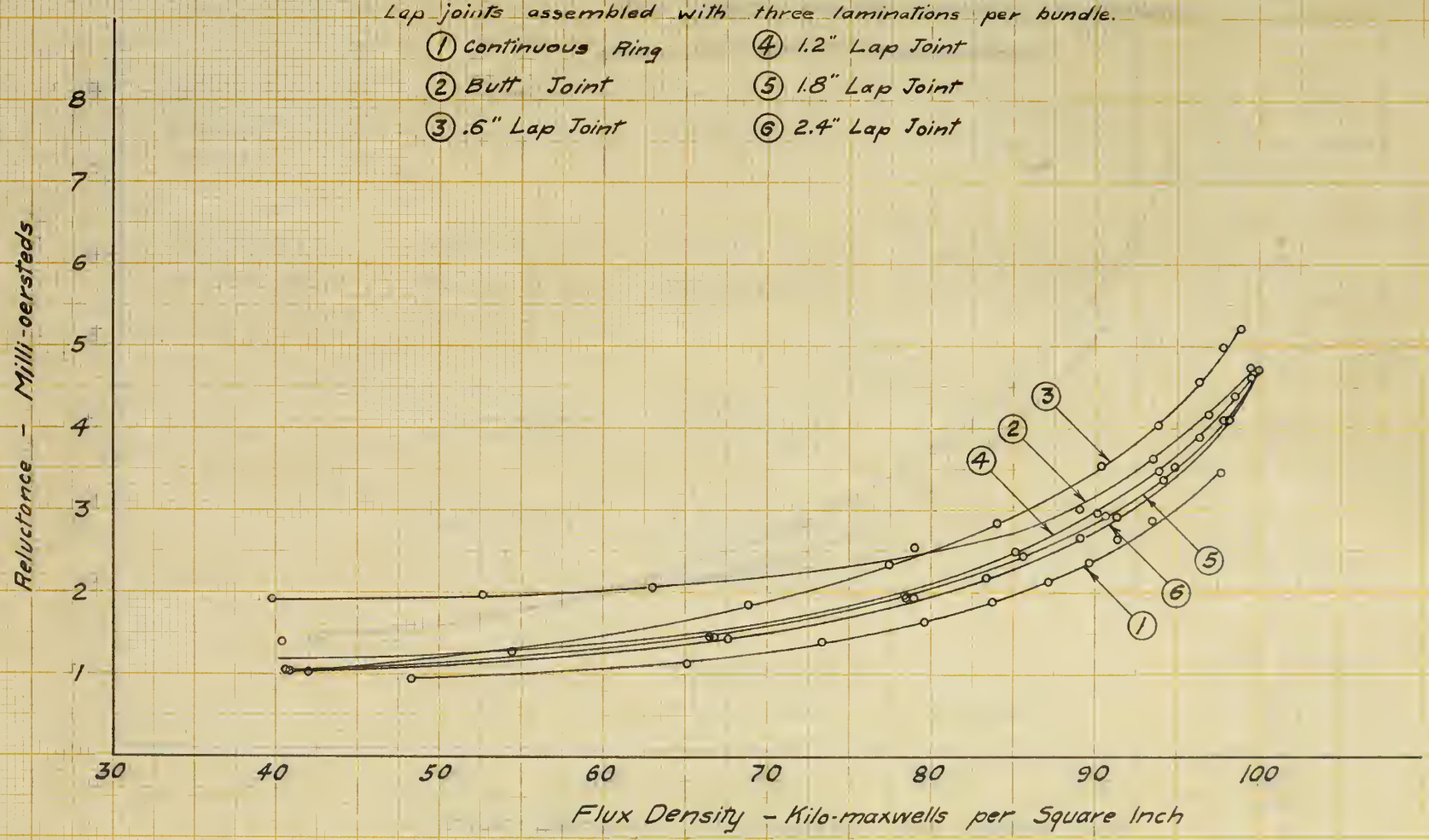
Amperes	Volts	Watts	Flux Density Kilomaxwells per Sq. In.	Reluctance Millioersteds
	1.2" Lap Joint			
.4	55.8	19.0	40.4	1.40
.8	91.8	34.0	66.5	1.46
1.2	108.0	45.0	78.3	1.98
1.6	117.6	54.0	85.1	2.50
2.0	124.4	60.0	90.1	2.96
2.4	129.6	65.0	93.9	3.49
2.8	133.0	70.0	96.4	3.90
3.2	136.0	74.9	98.5	4.40
3.4	137.2	75.2	99.5	4.62
	1.8" Lap Joint			
.4	56.0	15.0	40.6	1.06
.8	92.0	35.0	66.6	1.45
1.2	108.0	46.5	78.3	1.95
1.6	118.2	55.0	85.6	2.45
2.0	125.0	61.0	90.6	2.93
2.4	130.0	66.0	94.2	3.39
3.0	135.0	72.5	97.8	4.10
3.5	138.0	77.5	100.0	4.71
	2.4" Lap Joint			
.4	58.0	15.0	42.0	1.04
.8	93.4	35.0	67.6	1.43
1.2	109.0	46.5	79.0	1.93
1.4	115.0	51.0	83.3	2.18
1.8	123.0	57.0	89.1	2.68
2.0	126.0	62.0	91.3	2.91
2.5	131.0	76.0	94.9	3.53
3.0	135.4	72.5	98.1	4.10
3.5	138.0	77.5	100.0	4.73

GRAPH III

RELUCTANCE OF MAGNETIC CIRCUITS.

Alternating Current Method.

Lap joints assembled with three laminations per bundle.



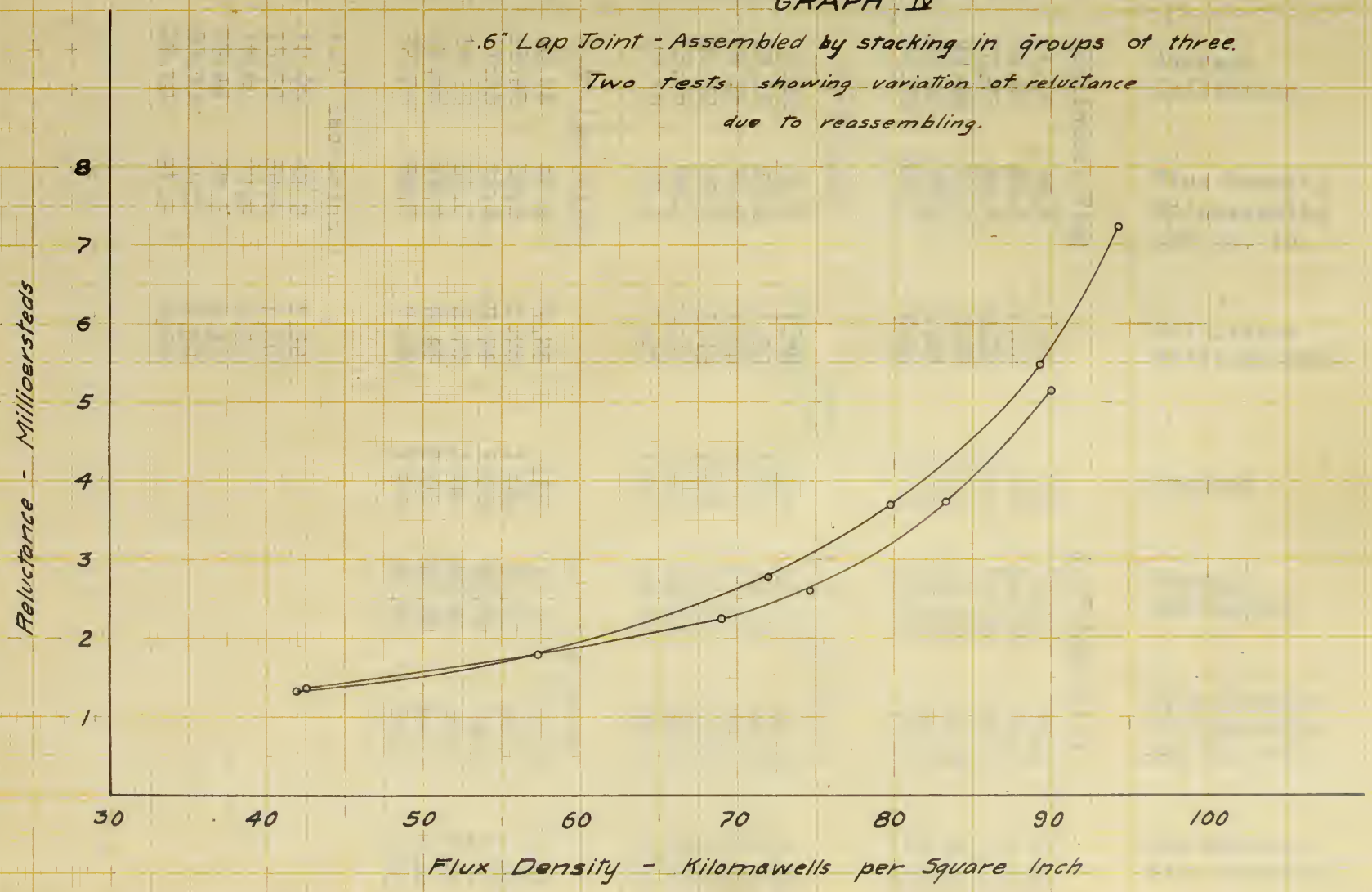
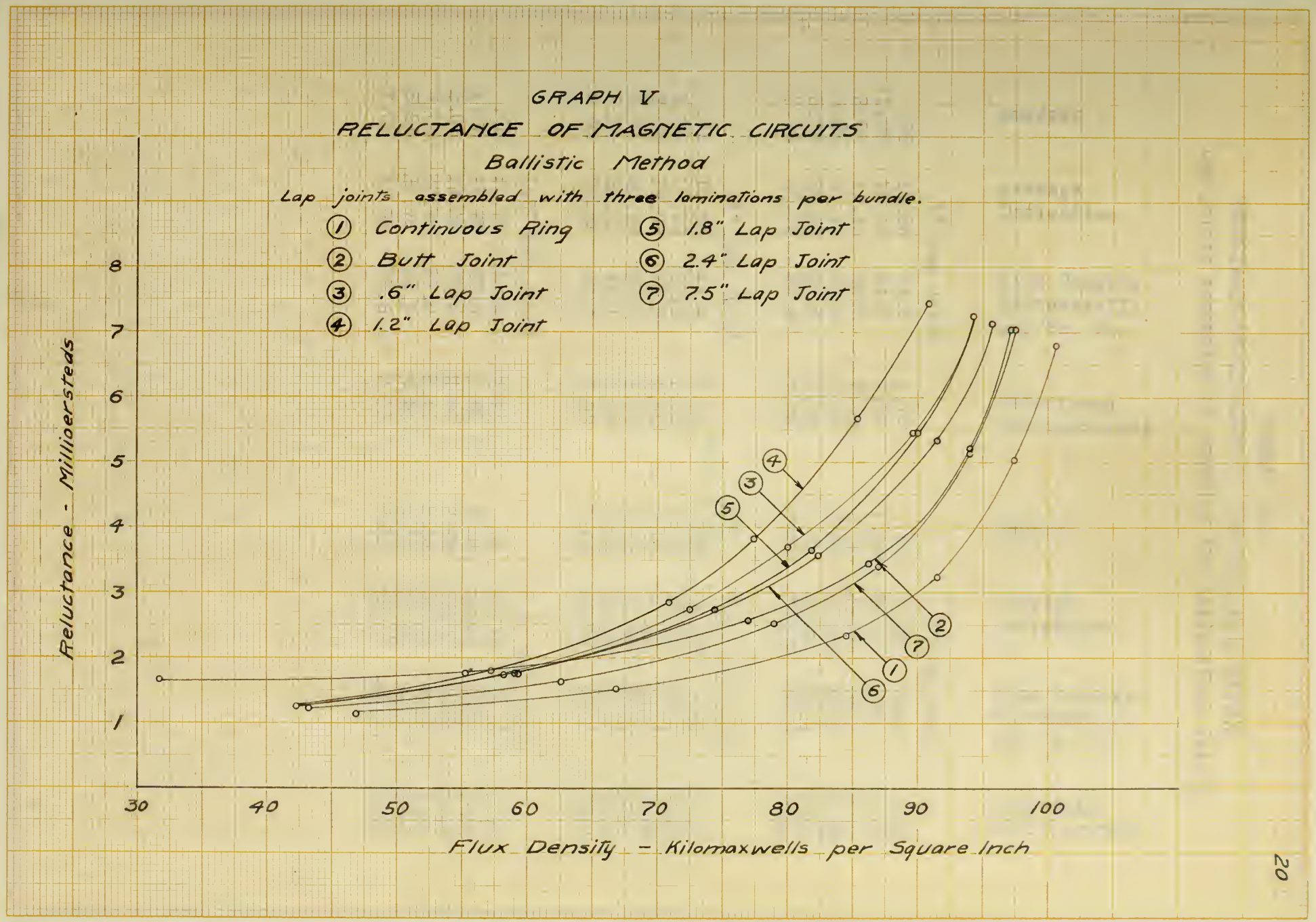

GRAPH IV
.6" Lap Joint - Assembled by stacking in groups of three.
Two tests showing variation of reluctance
due to reassembling.
Reluctance - Millioersteds
8
7
6
5
4
3
2
1
30
40
50
60
70
80
90
100
Flux Density - Kilomawells per Square Inch

TABLE II

RELUCTANCE OF CIRCUITS BY THE BALLISTIC METHOD

Lap joints assembled with three laminations per group.

Amperes	Average Deflection	Flux Density Kilomaxwells per Sq. In.	Reluctance Millioersteds
	Continuous Ring		
.55	11.15	46.9	1.14
1.05	15.90	66.8	1.53
2.05	20.25	84.5	2.36
3.05	22.00	91.5	3.23
5.05	23.60	97.4	5.04
7.05	24.50	100.7	6.80
	Butt Joint		
.55	7.58	31.7	1.68
1.05	13.15	55.3	1.78
2.05	18.35	77.0	2.59
3.05	20.70	86.3	3.43
5.05	22.68	94.0	5.21
7.05	23.55	97.1	7.05
	.6" Lap Joint		
.55	10.05	42.3	1.26
1.05	13.95	58.2	1.75
2.05	17.30	72.5	2.74
3.05	19.15	80.0	3.70
5.05	21.55	89.6	5.45
7.05	22.75	94.2	7.25
	1.2" Lap Joint		
.55	10.05	42.3	1.26
1.05	13.50	56.8	1.80
2.05	16.60	70.8	2.85
3.05	18.45	77.3	3.82
5.05	20.70	85.3	5.69
7.05	22.10	91.8	7.50
	1.8" Lap Joint		
.55	10.15	42.5	1.25
1.05	14.05	59.2	1.73
2.05	17.40	72.5	2.74
3.05	19.30	81.8	3.66
5.05	21.60	90.0	5.45
7.05	22.75	94.2	7.26
	2.4" Lap Joint		
.55	10.10	42.4	1.26
1.05	14.10	59.3	1.72
2.05	17.75	74.4	2.72
3.05	19.80	82.4	3.59
5.05	22.00	91.5	5.35
7.05	23.10	95.6	7.15
	7.5" Lap Joint		
.55	10.35	43.2	1.23
1.05	14.90	62.6	1.63
2.05	18.92	79.0	2.51
3.05	20.85	87.0	3.40
5.05	22.68	94.0	5.15
7.05	23.65	97.5	7.03


GRAPH V
RELUCTANCE OF MAGNETIC CIRCUITS
Ballistic Method
Lap joints assembled with three laminations per bundle.
1 Continuous Ring
2 Butt Joint
3 .6" Lap Joint
4 1.2" Lap Joint
5 1.8" Lap Joint
6 2.4" Lap Joint
7 7.5" Lap Joint
Reluctance - Millioersteds
1
2
3
4
5
6
7
8
30
40
50
60
70
80
90
100
Flux Density - Kilomaxwells per Square Inch

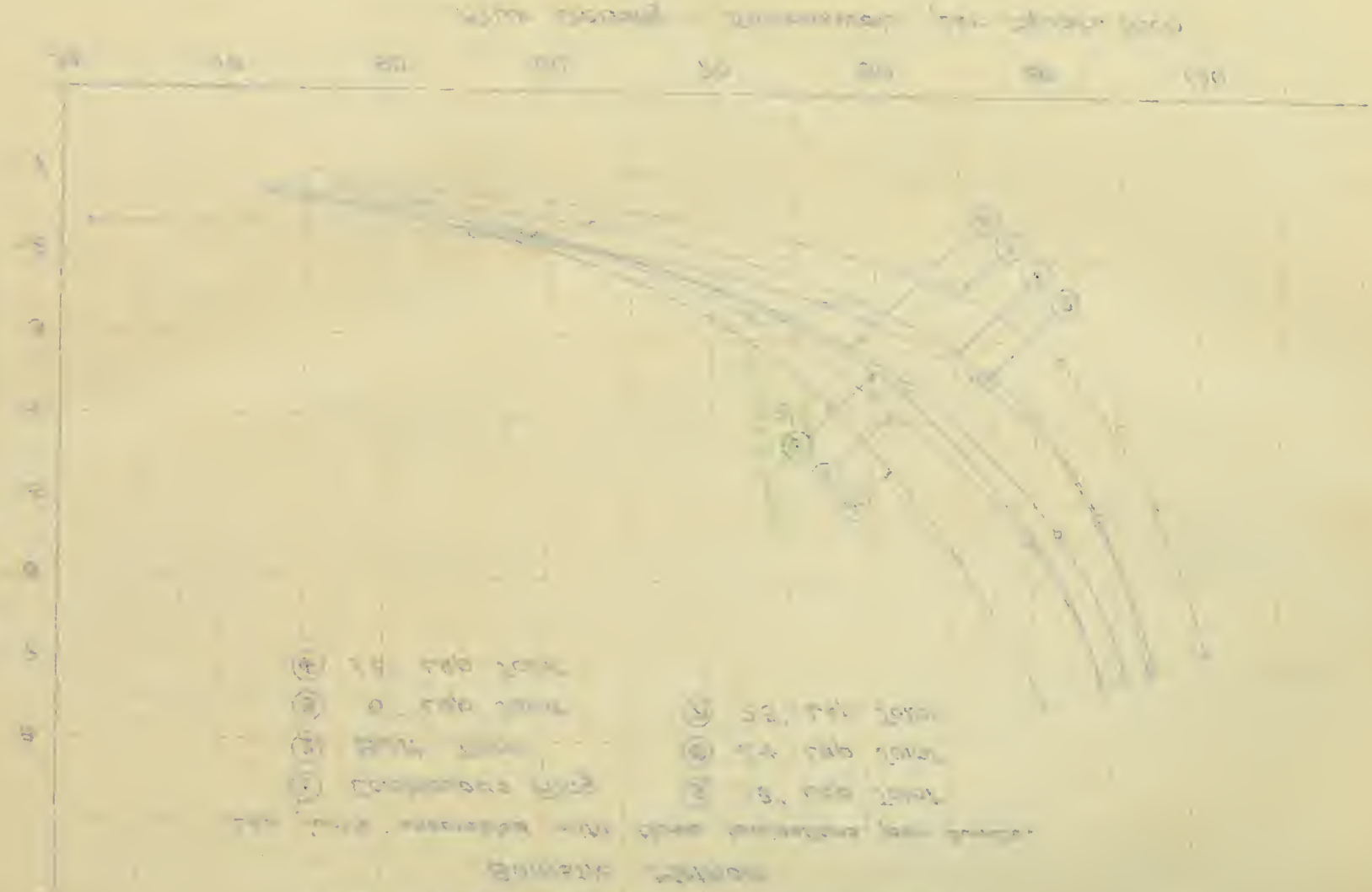
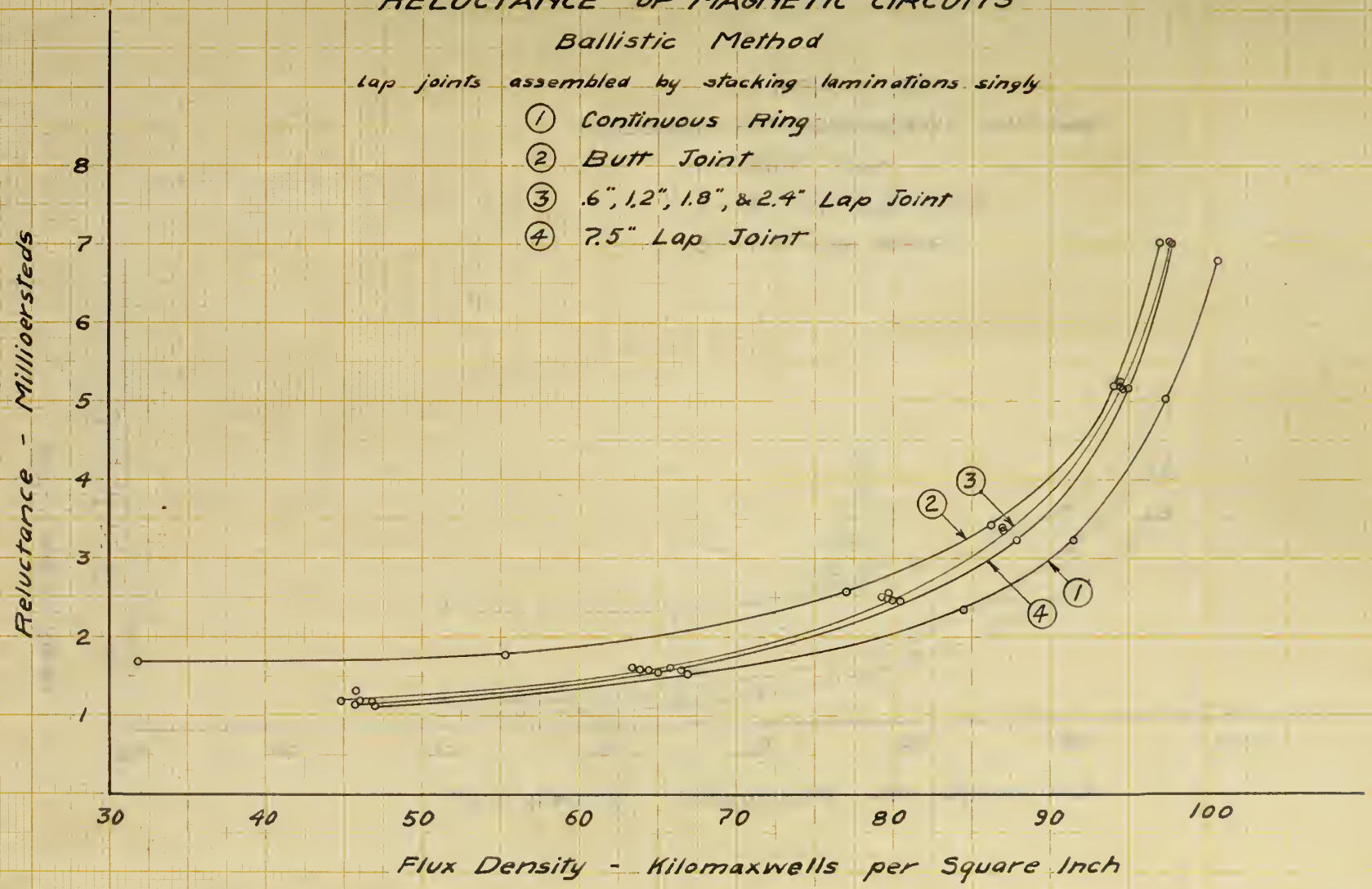


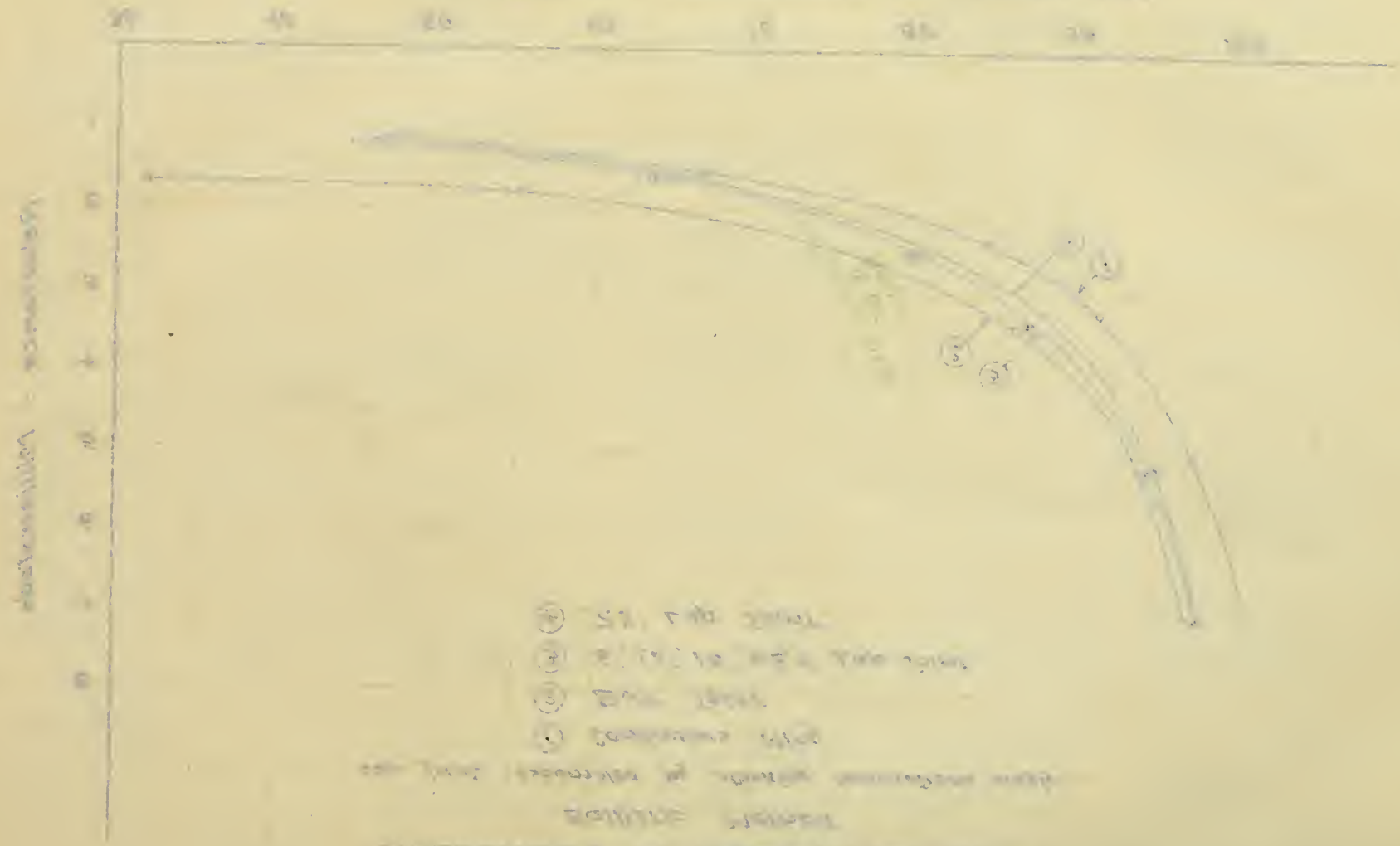
TABLE III

RELUCTANCE OF CIRCUITS BY THE BALLISTIC METHOD

Lap joints assembled by stacking the laminations singly.

Amperes	Average Deflection	Flux Density Kilomaxwells per Sq. In.	Reluctance Millioersteds	Amperes	Average Deflection	Flux Density Kilomaxwells per Sq. In.	Reluctance Millioersteds
	.1" Lap Joint				1.8" Lap Joint		
.55	10.85	44.9	1.19	.55	10.58	44.3	1.32
1.05	15.40	64.5	1.58	1.05	15.10	63.4	1.61
2.05	19.15	80.5	2.46	2.05	19.05	79.5	2.50
3.05	21.15	87.9	3.22	3.05	20.93	87.0	3.38
5.05	22.85	94.7	5.18	5.05	22.70	94.1	5.20
7.05	23.75	97.8	7.00	7.05	23.58	97.6	7.03
	.6" Lap Joint				2.4" Lap Joint		
.55	10.65	44.4	1.19	.55	10.63	44.4	1.19
1.05	15.10	63.4	1.61	1.05	15.30	64.1	1.59
2.05	19.00	79.3	2.50	2.05	19.20	80.0	2.48
3.05	20.90	87.0	3.40	3.05	21.00	87.0	3.38
5.05	22.70	94.1	5.20	5.05	22.60	94.5	5.24
7.05	23.65	97.6	7.03	7.05	23.65	97.6	7.03
	1.2" Lap Joint				7.5" Lap Joint		
.55	10.78	45.1	1.18	.55	10.93	45.7	1.16
1.05	15.20	63.8	1.60	1.05	15.55	65.0	1.56
2.05	19.08	79.5	2.50	2.05	19.30	80.5	2.46
3.05	20.90	87.0	3.40	3.05	21.05	87.7	3.23
5.05	22.75	94.5	5.20	5.05	22.85	94.6	5.18
7.05	23.65	97.6	7.03	7.05	23.73	97.6	7.03


GRAPH VI
RELUCTANCE OF MAGNETIC CIRCUITS
Ballistic Method
Lap joints assembled by stacking laminations singly
① Continuous Ring
② Butt Joint
③ .6", 1.2", 1.8", & 2.4" Lap Joint
④ 7.5" Lap Joint
Reluctance - Millioersteds
1
2
3
4
5
6
7
8
30
40
50
60
70
80
90
100
Flux Density - Kilomaxwells per Square Inch



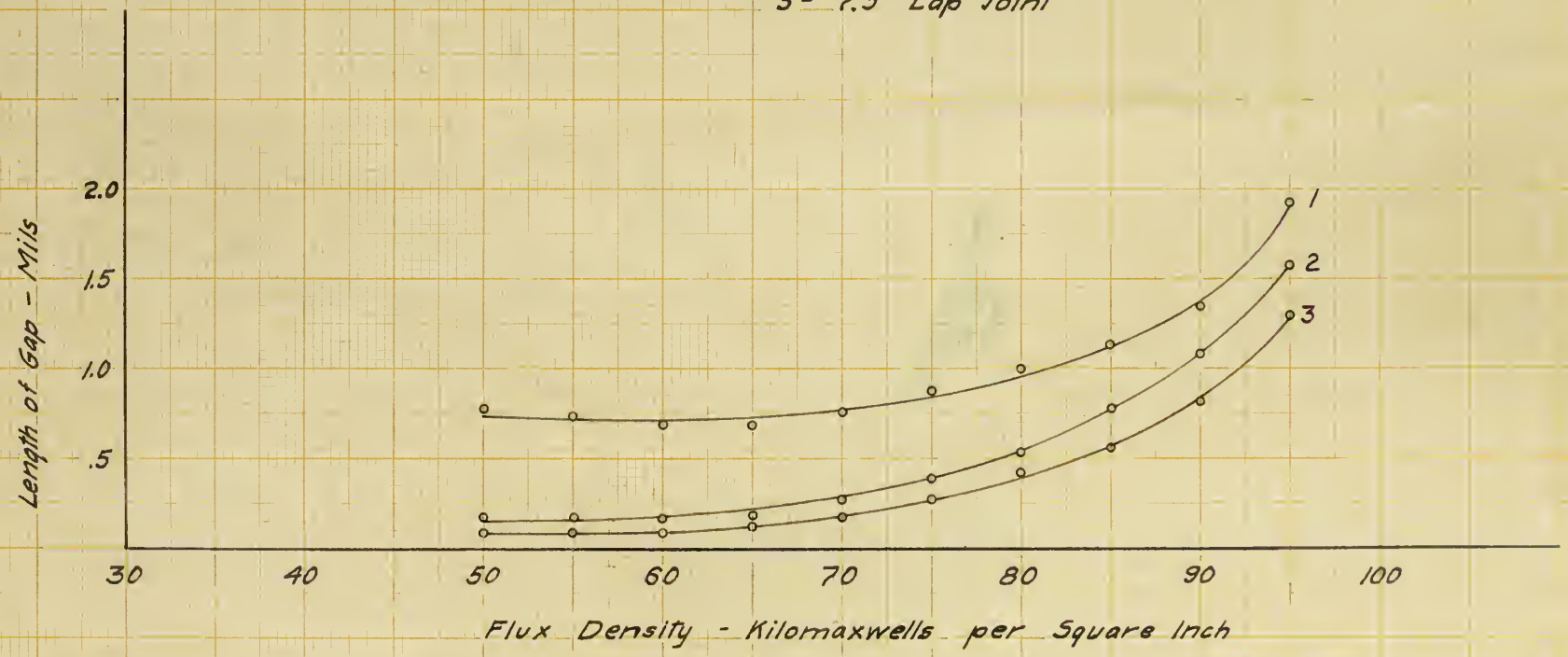
GRAPH VII

LENGTH OF EQUIVALENT AIR GAP

1 - Butt Joint

2 - .6"-2.4" Lap Joint

3 - 7.5" Lap Joint



UNIVERSITY OF ILLINOIS-URBANA
3 0112 082199263